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(54) Title: MICROFABRICATED TORSIONAL CANTILEVERS FOR SENSITIVE FORCE DETECTION
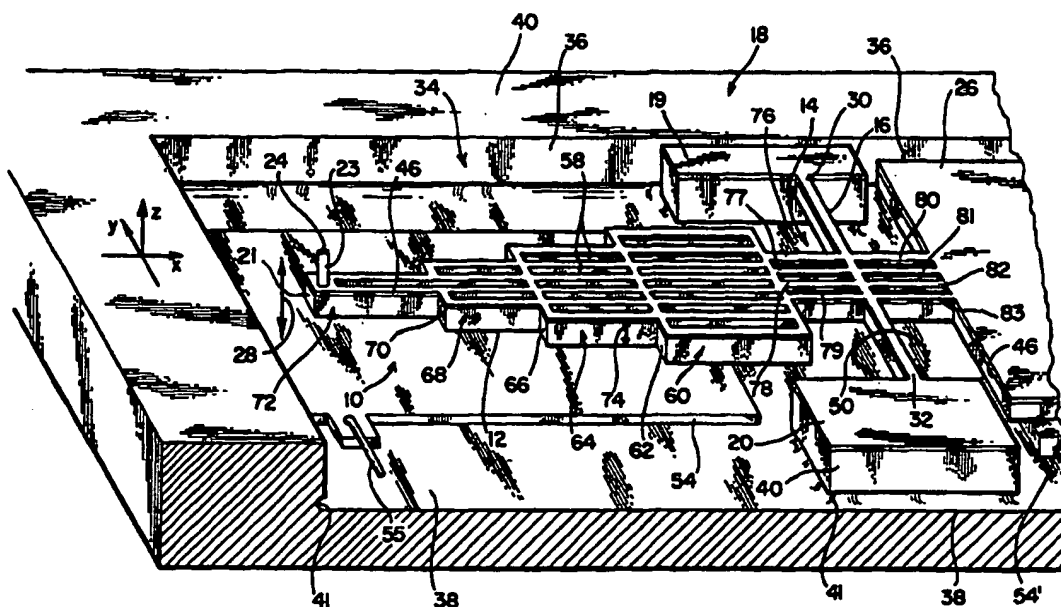
(57) Abstract

A torsional cantilever is microfabricated for reduced size to increase its resonance frequency, increase its scanning speed, and permit fabrication of large numbers in an array to provide parallel scanning. The cantilever may incorporate a tip for highly sensitive force detection. The device preferably includes a cantilever arm and a counterbalance mounted on opposite sides of a laterally extending torsional beam fixed at its outer ends. Sensors detect rotation of the cantilever arm and may provide control of sensor locator through a feedback loop.

MICROFABRICATED TORSIONAL CANTILEVERS FOR SENSITIVE FORCE DETECTION

Background of the Invention

5   This application claims the benefit of
U.S. Provisional Application No. 60/001,296, filed
July 20, 1995, the disclosure of which is
incorporated herein by reference.

          The present invention relates, in
10   general, to torsional cantilevers, and to methods
for fabricating such cantilevers.   More
particularly, the invention relates to a high
aspect ratio, single crystal silicon torsional
cantilever having a cantilever moment arm mounted
15   on a torsional support beam, to arrays of such
cantilevers, and to a process for fabricating such
a cantilever which is compatible with processes
for making conventional silicon integrated
circuits.

20   Since their development in the early
1980s, scanning probe microscopes have become
important tools for surface analysis and surface
modification. The unique applications of scanning
probe microscopes include imaging and manipulating
25   single atoms, measuring forces on the atomic
scale, and performing nm-scale lithography. At
the center of the family of scanning probe

microscopes are the scanning tunnelling microscope

(STM) and the atomic force microscope (AFM).

These macroscopic scanned probe instruments, for

the most part, use large piezoelectric actuators

5   to position a sensing tip or a probe in three

dimensions (xyz) and thus to provide relative

motion between the tip and a sample surface.

However, the size of these microscopic instruments

limits their performance, for the mass of the tip-

10   actuator structure produces low resonant

frequencies and low scanning rates.   More

importantly, these large instruments cannot be

easily integrated into arrays for high speed

scanning and atom manipulation, for information

15   storage,   or   for   high   throughput,   nm-scale

lithography systems.

A cantilever of some sort is often used

in macroscopic force microscopy to monitor the

variations   in   forces   which   represent   the

20   interaction between a tip and a sample. In such

cases, the cantilever is usually a silicon nitride

"V" cantilever which, for example, may be 0.6 to

2 micrometers thick, may be 100 to 200 micrometers

long, and which may have a spring constant of

25   between about 0.03 and 3 N/m for contact mode

imaging. See, for example, T.R. Albrecht et al,

3

J. Vac. Sci. Technol. A8, 3386 (1990). For non-contact mode imaging, the cantilever may be silicon with a spring constant of about 1 to 100 N/m, as described by Wolter et al, J. Vac. Sci.

5   Technol. B9, 1353 (1991). In order to obtain a high degree of sensitivity, a low spring constant k and a high Q is needed for such cantilevers, and attempts have been made to accomplish this through the use of thin films. However, it is necessary

10   to make the cantilever very thin in order to achieve a low spring constant with a thin film; for example, magnetic resonance force detection has been performed using a cantilever (without an integrated tip) that was only 900 Å thick, and

15   which had a spring constant of 10^{-3} N/m. However, the fabrication and use of such thin cantilevers poses many problems, including the problem of tip integration, problems with internal stress, and problems in making electrical connections and in

20   amplifying the resulting signals.

         For many years, torsion has been used as a technique for highly sensitive measurements of force interactions; for example, measurement of Coulomb's torsional balance for electrostatic

25   forces and Cavendish's balance for gravitation. Furthermore, torsional resonators have been used

4

as high-Q resonators to study a variety of physical properties such as dissipation and visoelasticity. Such devices have been widely used because cantilevers, resonators or balances

5   can be made symmetric with respect to their center of mass, with the result that lateral vibrations of the support do not couple to the torsional mode of the sensor device. In the case where the measuring device includes a spring, lateral modes

10   of the spring can be made much stiffer than the torsional mode without affecting the torsional behavior, thus making torsional measurements desirable.

Torsional cantilevers are known to

15   provide a viable option in scanning force microscopy. However, such cantilevers have, in the past, been assembled by hand, using cleaved pieces of silicon, carbon fibers or tungsten wire, and epoxy. Such devices did not incorporate

20   integrated tips and, although microfabricated cantilevers have been demonstrated, such devices exhibited a lateral stiffness which was as soft as, or softer than that of a V-shaped cantilever. The lack of sufficient lateral stiffness can

25   result in unwanted "stick-slip" behavior as the cantilever is scanned across samples.

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Summary of the Invention

The present invention is directed to an improved torsional cantilever which is microfabricated for reduced size to increase its resonant frequency and thereby increase its scanning speed, and to permit the fabrication of large numbers of devices in a unit area to provide parallel scanning of a surface. This microfabricated cantilever may incorporate an integrated tip so that it is particularly adapted to provide highly sensitive detection of forces. Further, the cantilever is integral with a substrate which may incorporate conventional integrated circuits to which the cantilever and/or tip may be electrically connected. In the preferred form of this invention, the substrate material is a single crystal silicon, and the cantilever structure preferably is fabricated as a microelectromechanical (MEM) device by the single crystal reactive etch and metalization (SCREAM-I) process described in copending U.S. Patent Application Serial No. 08/312,797 filed September 27, 1994 of Kevin A. Shaw, Z. Lisa Zhang and Noel C. MacDonald, the disclosure of which is hereby incorporated herein by reference (Docket No. CRF D-1307C). This fabrication process allows

6

integration of the cantilever structure on a single crystal silicon substrate carrying pre-existing integrated circuits, and allows the cantilever to be formed with an integral submicron

5   tip for use, for example, in scanning surfaces to be measured in scanning probe microscopy, or in other applications.

The process also permits incorporation of motion control devices such as capacitors in

10   the cantilever device for producing and/or for controlling scanning motions in x, y, and z directions with respect to the axis of the cantilever, with such capacitors also being available to measure tip motion in response to

15   forces to be detected. The process of the present invention also permits incorporation of other sensors, such as piezoresistive devices, diodes or transistors within the cantilever structure for use, for example, in detecting motion or in

20   amplifying electrical currents detected by the tip. The integration of all of these features produces a scanning torsional cantilever that is extremely compact, which requires no external deflection sensor, and which is suitable for use

25   in a variety of atmospheres and temperatures, as well as for use in dense array architectures of

scanned probe instruments for information storage
and molecular or atomic manipulation.

The torsional cantilever structure is a
basic building block for micromechanical scanning
5   probe microscopes, and can be fabricated with an
integrated tip in a 100 μm x 100 μm square area.
The structure includes a torsional support beam
which is secured at each of its ends to a
substrate;   preferably,   the   support   beam   is
10   integrally formed with the substrate. A sensor
arm, or cantilever moment arm, consisting of a
rigid grid of single crystal silicon beams is
microfabricated integrally with the support beam,
and extends generally horizontally outwardly from
15   the beam in cantilever fashion, the beam support
and sensor arm lying in a horizontal x-y plane and
perpendicular to each other. The outermost, or
free end of the sensor arm carries a sensor tip
which interacts with a sample to be measured.

20   The cantilever may be made to pivot about its
support beam by electrodes fabricated on the
substrate   beneath   the   cantilever   structure.
Alternatively,   the   structure   may   incorporate
interdigitated   comb   capacitor   structures   to
25   provide controlled motion of the cantilever. This
pivotal   motion   of   the   cantilever   about   the

8

torsional support beam provides the out-of-plane
motion required to enable the tip to track a
surface. If desired, a small xy scanner may be
integrated into the cantilever structure for

5   precise lateral positioning of the tip. Forces
applied to the tip, for example in the vertical
(z) direction, deflect the tip, and this motion is
transferred by the sensor arm to the support beam
in the form of a torsional force applied about the

10   horizontal axis of the support beam. The
torsional force applied to the support beam by the
cantilever moment arm can be measured in a variety
of ways to provide an accurate measure of the tip
force. For example, the relative motion of

15   interdigitated capacitor plates, or the motion of
the cantilever with respect to an underlying
electrode can be measured as a change in
capacitance. Deflection can also be measured by
a piezoresistor produced in the support beam, as

20   by implanting an n-type region into a p-type
substrate or implanting a p-type region into an n-
type substrate. The doped region forms a
resistance which changes due to stress produced in
the support beam by relative rotation of the

25   torsion arm.

9

The measurement of rotation can also be accomplished by another stress-sensitive device based on the piezojunction effect. In this case, a sensor diode is formed by implanting an n-type

5   region in the p-type substrate silicon at the junction of the torsional support beam with a fixed mesa on which the beam is mounted. Contacts are made to this implanted region and to the adjacent substrate. Stress in the support beam

10   causes a change in current through this diode, and changes in the current can be measured.

The cantilever moment arm structure of the invention can be utilized whenever out-of-plane or rotational actuators or force sensors are

15   required. Such an actuator may be used, for example, in an accelerometer, wherein an asymmetric design, with more mass on one side of the cantilever than on the other, provides a device which will be sensitive to acceleration in

20   directions out of the plane of the cantilever and the substrate on which it is mounted. The actuator can also be used in force microscopy employing a symmetric design which balances the applied force so that the device will be highly

25   sensitive to changes in a force acting on one side of the cantilever, and not on the other.

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By integrating a tip on the free end of
the cantilever moment arm in a microscope, the
torsional cantilever becomes a tip-to-surface
force center in a scanning force microscope. The

5   out-of-plane motion, or torsional cantilever
motion (in the z direction), also enables the tip
to track surface topography. If desired, the
cantilever may carry a mirror or an interferometer
to provide accurate measurement of out-of-plane or

10   rotational motion, or one or more of the sensors
described above can measure and/or control this
motion.

With the torsional cantilever beam
established as a building block, an array of beams

15   can be fabricated, wherein cantilevers can be
provided at 100 μm intervals to provide, for
example, a 10x10 array of cantilevers in a 1 mm by
1 mm square area. Such an array allows an entire
1 mm by 1 mm sample to be scanned for imaging or

20   manipulation by moving the support mechanism only
100 μm in x and y directions.

The array can be made in several
configurations. For example, torsional
cantilevers can be made individually movable in

25   the z direction while the sample is scanned in x
and y directions. Alternatively, the cantilevers

11

can be fabricated to be movable in the z direction
as part of a micromechanical structure that is
scannable in the x direction, with the sample
being scannable in the y direction. In another

5   configuration, the z cantilevers can be fabricated
as part of a micromechanical stage that is
scannable in x and y directions, with the sample
remaining stationary. The sample can be a chip
with a bare surface or a compliant surface, or can

10   be an active MEM device. Alternatively, the
sample can be placed on or bonded to a chip which
carries an array of microscanned probe devices,
wherein the torsional cantilever elements which
make up the probe provide enough out-of-plane (or

15   z-direction) motion to allow the tips to contact
the surface. To facilitate this, sample support
pillars or posts are fabricated on the chip which
carries the array, with the pillars having the
same height as, or being a little taller than, the

20   tips.

A large number of electrical connections
are required in an array of cantilevers to carry
control signals for individually moving the
cantilever arms or for carrying sensor output

25   signals from each arm. Transistors for switching
among various devices can reduce the number of

12

connections, and such switches can be in the form
of normal planar IC transistors fabricated on the
silicon substrate.   Metal pathways along the
substrate provide the necessary connections.

5   Suspended transistors in the silicon beams can
also be used for switching, amplification, and
logic, and electrical isolation can be provided by
oxide segments in the beams.

The cantilevered arms and arrays of such

10   arms can be used in a wide range of applications.
In addition to scanning of images and the
manipulation of surfaces at atomic and near-atomic
scales, the devices and arrays of the invention
can be used for high density information storage,

15   in the range of a terabit per cm^2, for molecular
manipulation instruments, for field emission (e-
beam) instruments, and for microlithographic or
micromachining tools.

20   **Brief Description of the Drawings**

The foregoing, and additional objects,
features and advantages of the present invention
will become apparent to those of skill in the art
from the following detailed description of

25   preferred embodiments thereof, taken in

13

conjunction with the accompanying drawings, in which:

Fig. 1 is a partial perspective view in diagrammatic form of a torsional cantilever device
5   in accordance with the present invention;

Fig. 2 is a top plan view of the cantilever device of Fig. 1;

Figs. 3(a) through 3(h) illustrate a process for fabricating sensor tips on the device
10   of Fig. 1;

Figs. 4(a) and 4(b) are diagrammatic illustrations of a metallization process used in the device of Fig. 1;

Fig. 5 is a partial, enlarged view of
15   the cantilever structure of Figs. 1 and 2;

Fig. 6 is an enlarged, partial view of the torsional support beam for the device of Fig. 1;

Fig. 7 is a graphical illustration of
20   curves representing the relationship of effective spring constant to cantilever length for different cantilever cross-sectional widths "a" each having a cantilever cross-sectional height "b" of $10\mu m$;

Fig. 8 is a top plan view of a second
25   embodiment of the cantilever device of the present invention;

14

Fig. 9 is a top plan view of a third embodiment of the cantilever device of the present invention, utilizing torsion control electrodes;

Fig. 10 is a cross-sectional view taken along lines 10-10 of Fig. 9;

Fig. 11 is a fourth embodiment of the cantilever device of the present invention, utilizing comb-type capacitors for motion sensing and compensation;

Fig. 12 is a fifth embodiment of the device of the present invention, utilizing comb-type capacitors;

Fig. 13 is a partial, enlarged perspective view of a modified comb capacitor for the device of Fig. 12;

Fig. 14 illustrates a first alternative version of the comb capacitor of Fig. 13;

Fig. 15 illustrates a second alternative version of the comb capacitor of Fig. 13;

Fig. 16 is a sixth embodiment of the device of the present invention, combining the features of Figs. 9 and 10;

Fig. 17 is a diagrammatic illustration of the use of the torsional cantilever device of the present invention in an atomic force microscope;

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Fig. 18 is a photomicrograph of the torsional cantilever device of the present invention incorporated in an capacitor-driven xy stage configuration;

5   Fig. 19 is a diagrammatic illustration of an array of cantilevered sensors mounted for motion in an xy plane, with individual cantilevers being movable in the z direction;

Fig. 20 is an enlarged, partial top plan

10   view   of   a   torsional   cantilever   device incorporating piezoresistive sensors;

Fig. 21 is a cross-section along lines 21-21 of Fig. 20;

Fig. 22 is an enlarged, partial top plan

15   view   of   a   torsional   cantilever   device incorporating diode sensors; and

Fig. 23 is a cross-sectional view taken along lines 23-23 of Fig. 22.

20   <u>Description of Preferred Embodiments</u>

Turning   now   to   a   more   detailed consideration of the present invention, there is illustrated in Fig. 1 a perspective view of a microfabricated, highly sensitive force detecting

25   torsional cantilever device 10 incorporating an e l o n g a t e d   t o r s i o n a l l y - m o u n t e d

16

microelectromechanical (MEM) cantilever moment arm
generally indicated at 12. This device has a wide
range of applications, but will be described
herein for convenience as being used as a force
5   sensor in scanning probe microscopy. The
cantilever moment arm portion 12 is mounted at a
first, or near end 14 to the center of a laterally
extending torsional support beam 16. In the
illustrated embodiment, the opposite ends of the
10   beam 16 are supported on, and preferably are
integral with, a substrate 18 as at support mesas
19 and 20. The arm 12 is integral with beam 16
and in its preferred form is formed of a grid of
longitudinal and lateral beams, as illustrated in
15   Fig. 1, the arm extending from its near end 14
generally horizontally forwardly from the mounting
beam 16 to a far, or distal, end 21 along a
longitudinal axis 22 (Fig. 2) which is
perpendicular to beam 16. An upwardly-extending,
20   generally vertical, nanometer-scale sensing tip 23
is formed on the distal end 21 of the cantilever
moment arm in the preferred form of the invention.
This sensing tip is generally conical, tapering
upwardly and inwardly to an extremely small
25   diameter, on the order of one atom, at its end 24.
The arm 12 and beam 16 lie in an x-y plane, with

17

tip 22 extending perpendicularly to the plane, in a z direction.

Also mounted on lateral support beam 16, but on the opposite side thereof from arm 12, is a counterweight 26 which is also fabricated as a grid of longitudinal and lateral beams (not shown in Fig. 1), and which is of sufficient size and weight to produce a counterbalancing mass for the cantilever arm so as to make the arm more sensitive to, and responsive to, forces applied to tip 23. The counterweight 26 serves as an extension of cantilever moment arm 12 so that arm 12 and counterweight 26 rotate together about a lateral axis 27 of the beam 16. Axis 27 lies in the x-y plane of arm 12 and beam 16, with axis 27 being perpendicular to the longitudinal axis 22 of arm 12. Rotation of arm 12 and weight 26 occurs upon application of vertical forces in the direction of arrow 28 in Fig. 1; that is, upon application of forces in the z direction to the tip 23.

The torsional cantilever device 10, which includes the moment arm 12, the lateral torsional mounting beam 16, the tip 23 and the counterweight 26, is fabricated by the SCREAM-I process described in the aforesaid U.S.

18

Application Ser. No. 08/312,797, discussed above.
This process includes a reactive ion etching
process for fabricating suspended, released,
single crystal silicon microelectromechanical
5   (MEM) structures, with feature dimensions as small
as 250 nm and with arbitrary structure
orientation, from the single crystal silicon wafer
or substrate 18. During the fabrication process,
the torsional cantilever structure 10 is released
10   from the underlying substrate so that it is
mechanically spaced from, is supported over, and
is generally parallel to, the underlying
substrate. The cantilever structure 10 is
connected to the substrate only at support regions
15   30 and 32, where the lateral beam 16 intersects
and is integral with mesas 19 and 20 formed during
the fabrication process, or is integral with the
sidewalls of a cavity formed in the substrate 18.
The cantilever device 10 is conveniently referred
20   to as a released structure.

        During the SCREAM-I fabrication process,
the beams which make up arm 12, beam 16, and
counterweight 26 are lithographically defined in
a single etch mask and the regions surrounding the
25   defined structure are removed from the substrate
by reactive ion etching (RIE) to form surrounding

19

trenches which together produce a cavity 34 having

vertical walls 36 in the substrate 18. The cavity

also surrounds the support mesas 19 and 20 which

are formed in the substrate, as illustrated.

5   Thereafter, a second RIE step undercuts and

releases the defined structure and in addition

undercuts the support mesas and surrounding

substrate mesa. The cavity 34 thus incorporates

a generally vertical side wall 36, which surrounds

10   the cavity 34 in which cantilever device 10 is

located and a floor 38 which underlies the

cantilever and which preferably lies in a

horizontal (x-y) plane below and substantially

parallel to the cantilever 10. The side wall 36

15   surrounding the cavity 34 defines not only the

support mesas 19 and 20, but also a substrate mesa

region illustrated at 40 in Fig. 1. The side wall

36, as well as the walls of the mesas 19 and 20,

are undercut, as illustrated at 41, during the

20   release step. The substrate mesa region 40 may

incorporate one or more integrated circuits, such

as those generally indicated at 42 and 44 in Fig.

2, which may be fabricated in conventional manner

prior to the formation of the cantilever 10.

25   In the SCREAM-1 process, a metal layer

46 may be deposited on the released structure and

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the surrounding substrate. This metal layer is
discontinuous at the trenches to separate the
metal on the released elements from the metal on
the substrate both mechanically and electrically.
5   Furthermore, the undercut portions 41 prevent
metal deposited on the floor of the cavity from
being electrically connected to the metal on the
mesas.

          The SCREAM-I process is a low
10   temperature process which is compatible with
conventional integrated circuit processes, and
thus with preexisting integrated circuits on the
substrate. Thus, a substrate, or wafer, may first
be processed in conventional manner to first
15   provide integrated circuits which are to be used
to control or to sense a cantilever sensor
structure. A space is left on the wafer for
s u b s e q u e n t   f a b r i c a t i o n   o f   t h e
microelectromechanical structure of the present
20   invention by the SCREAM-I process. This process
will not damage the integrated circuits, and the
SCREAM-I process provides suitable metalization to
permit selected electrical interconnection between
the cantilever structure and the preexisting
25   integrated circuits.

21

In the preferred form of the invention, the
cantilever arm 12 is provided with a high aspect
ratio sensor tip 23 which is formed before the
above-described cantilever fabrication steps. In
5   one process for making the tip illustrated in
Figs. 3(a)-3(b), an n-type, P-doped, 18-40 ohm-cm,
(100) oriented single crystal silicon substrate is
subjected to ion implantation by an As dose of
$5x10^{14}/cm^2$ at 30 keV to form an n^+ layer. A
10 dielectric stack consisting of a 20 nm layer of
thermal oxide, a 150 nm layer of LPCVD nitride and
a 600 nm layer of PECVD oxide is formed on the top
surface of the substrate, as illustrated in Fig.
3(a), and a 700 nm film of KTI-OCG photoresist is
15 patterned and exposed in a GCA 4800 DSW wafer
stepper, to produce a resist pattern (Fig. 3(a)).
The resist pattern is transferred to the
dielectric stack by a CHF_3 reactive ion etch (RIE)
to produce a dielectric mask, as illustrated in
20 Fig. 3(b).   An SF_6 RIE etch then produces a
silicon cone under the dielectric mask. In one
example, a 4 sccm SF_6/2 sccm O_2 etch in a chamber
having a pressure of 5mTorr and under a DC bias of
-300V with an etch time of 5 minutes produced a
25 1.5 μm high circular cone underneath a 600nm
diameter dielectric mask.   A 100 nm silicon

22

dioxide layer is then thermally grown on the
exposed silicon surface (Fig. 3(c)).

        The foregoing was followed by a CHF_3-RIE
to etch any oxide on the horizontal surfaces (see
5   Fig. 3(c)), and a Cl_2-RIE vertical etch produced a
high aspect ratio (height to diameter ratio of at
least about 10 to 1) silicon post, as illustrated
in Fig. 3(d). This etch utilized a 50 sccm Cl_2/2
sccm BCl_3 etch at a chamber pressure of 20m Torr
10 and a DC bias of -400V. Thereafter, thermal
oxidation was used to sharpen the tip (Fig. 3(e)).
A typical sensor tip may have a height of about
10-20 μm, a diameter of about 1 μm, and a tip
radius of about 10nm.

15   If the tip is to be used as a force
sensor or for similar purposes, the foregoing
steps are followed by the above-described SCREAM
process to fabricate the cantilever 10. However,
in some cases it is desirable to utilize the tip
20 as a field emitter, in which case a self-aligned
electrode is formed in accordance with Figs. 4(f)
through 4(h). In this procedure, a metal contact
window is opened through the oxide layer, followed
by an As implant at 30 keV, 5×10^{15}/cm^2, and
25 annealing at 1000°C for 30 sec. Thereafter, a
sputter deposition of TiW covers the surface of

23

the substrate and the tip (Fig. 3(f)). A planarizing layer of KTI-OCG is spun on and baked at 90°C (Fig. 3(g)), and an O_2 plasma etch removes the photoresist until the TiW above the apex of

5   the tip is exposed (Fig. 3(g)). Finally, an SF_6-RIE etch of the TiW layer exposes the end of tip 23, with the tip being surrounded by a closely-spaced TiW electrode. Thereafter, the SCREAM-1 process is used to fabricate the cantilever 10.

10   The forces which are to be detected by the torsional cantilever 10 produce motion in the z-direction, as noted above, which is translated by tip 27 and moment arm 12 into a torsional motion about the lateral axis of rotation 27

15   corresponding to the lateral torsional beam 16. Vertical motion of tip 23 thus produces a torsional force on beam 16 in the direction of arrow 50 (Fig. 1), and this motion can be measured by a suitable sensor or sensors such as a plate

20   capacitor, multiple comb capacitors, piezoresistors, or devices such as transistors or diodes. For example, a capacitor for sensing vertical motion of arm 12 may be provided by formation of a metal electrode 54 on the floor 38

25   of the cavity 34 below arm 12, as well as an electrode 54' on the floor of the cavity under the

24

counterweight 26. These electrodes may be part of
the metal layer 46 deposited on the device during
the SCREAM process described above, but are
electrically isolated from the metal on the arm 12

5   and counterweight 26, as described above. The
electrodes 54 and layer 46 form opposed, spaced
capacitive plates which are connected through
metal connectors formed by patterning the metal
layer or are connected by wires such as wires 55

10   bonded to the electrode and to circuits such as
circuits 42 or 44.

The capacitance between the metal layer
46 on moment arm 12 and underlying metal layer 54
and the capacitance between the metal layer 46 on

15   counterweight 26 and the underlying metal layer
54' varies in opposite directions as the arm and
the counterweight rotate about beam 16 upon the
application of a force to tip 23. The rotation of
moment arm 12 thus produces a differential change

20   in capacitance which can be measured with great
accuracy to provide a highly sensitive detection
of the relative motion between arm 10 and the
substrate 18.

The metal capacitor electrodes 54 and

25   54' preferably are fabricated by sputtering metal
such as aluminum onto the substrate 18 containing

25

the released torsional cantilever structured, and
then evaporating aluminum, at an angle sufficient
to provide metal coverage under the beams as at 56
in Figs. 4(a) and 4(b), utilizing a rotating stage

5   57. Fig. 4(b) is an enlarged partial view of the
substrate, illustrating how the metal 56 passes
suspended elements such as individual beams 58
making up the cantilever structure. The metal is
then patterned using conventional photolithography

10   and reactive ion etching to shape the electrodes
and to provide surface electrical connections or
connector pads for interconnecting the electrodes
and adjacent circuitry.

       In place of the capacitive electrodes 54

15   and 54' capacitive comb-type elements may be
provided between the released torsional cantilever
structure and the substrate to sense or to produce
vertical motion of the cantilever. Such comb-type
sensors or drives may incorporate partially

20   oxidized silicon beams fabricated by the process
described in copending U.S. Patent Application
Serial No. 08/383,524 of Noel C. MacDonald and Ali
Jazairy, filed February 3, 1995, and entitled
"Masking Process for Fabricating Ultra-High Aspect

25   Ratio, Wafer-Free, Micro-Opto-Electromechanical

26

Structures" (CRF D-1689), the disclosure of which
is hereby incorporated herein by reference.

In the embodiment of the invention
illustrated in Figs. 1 and 2, the arm 12 has a
5   stepped shape of decreasing width and is made up
of a grid of individual longitudinal and lateral
beams 58 having high aspect ratios to provide the
desired rigidity, and thus the high spring
constant, needed to provide the desired accuracy
10   of measurement of applied forces at tip 23. Near
the base 14 of the arm 12, the arm is formed with
a relatively wide region 60 which steps down at
shoulder 62 to a second, slightly narrower region
64. This, in turn, steps down at shoulder 66 to
15   a still narrower region 68 and again steps down at
shoulder 70 to the narrowest region 72 on which
the tip 23 is mounted. The stepped, elongated
shape gives lateral stability to the sensing arm
12 (in the x-y plane) so that it is relatively
20   unaffected by lateral vibrations. The height of
each segment, indicated by arrow 74, is sufficient
to provide vertical rigidity, and to provide a
relatively large height to width ratio, or aspect
ratio, for the structure. It will be apparent, of
25   course, that numerous variations of this shape may

27

be used while still providing the desired
stability and rigidity for the arm.

In the preferred embodiment, the arm 12
is secured to the torsional beam 16 by a plurality
5   of longitudinally extending connector beams 76,
77, 78, and 79. These connector beams are formed
integrally with the arm 12 and with the torsional
beam 16, and have substantially the same height 74
as the arm 12 so as to maintain vertical rigidity
10   and high spring constant. Each of the connector
beams 76-79 preferably is thin, for light weight,
with a cross-section having a high aspect ratio;
that is, an aspect ratio of about 10 or 20 to 1.

Also, in the illustrated embodiment of
15   the invention the counterweight 26 is fabricated
as a generally rectangular structure having a
height approximately equal to the dimension 74 and
having an axial length along axis 21 and a lateral
width parallel to axis 27 sufficient to provide a
20   mass which will counter-balance the mass of the
arm 12. The counterweight 26 is mounted on arm 16
by connector beams 80-83 which are mounted on, and
which preferably are integral with, the transverse
cantilever beam 16, as well as being integral with
25   the counterweight 26. The beams 80-83 are similar
to and correspond to beams 76-79, and thus have

28

relatively high aspect ratios to provide the
required stability for the counterweight 26 and to
provide a high spring constant mounting for the
counterweight which will permit accurate
5   measurement of forces applied to tip 22.

        Although the metal layer 46 applied to
the surface of the cantilever 10 is illustrated in
Fig. 1 as a solid covering for the arm and
counterweight structure, a preferred form of the
10   invention is illustrated in Figs. 2 and 5. As
diagrammatically illustrated in Fig. 2, and as
best seen in Fig. 5, the moment arm 12 and the
counterweight 26 are formed as an open grid or
lattice work of thin, high aspect ratio beam
15   segments, such as the segments 58 illustrated in
an enlarged view in Fig. 5. Only a small number
of such beam segments are illustrated in Fig. 1
for clarity; however, as diagrammatically
illustrated in Fig. 2, the cantilever structure 10
20   preferably is made up of a large number of closely
spaced beam segments. The entire structure of
cantilever moment arm 12, torsional support beam
16, counterweight 26, and connector beams 76-83 is
fabricated from single crystal silicon using the
25   SCREAM-I process. Each beam segment thus has a
high aspect ratio on the order of about 10 to 1,

with the segments being released from, and spaced from, the underlying substrate floor 38 and spaced from the side walls 36. The ends of beam 16 are mounted to mesas 19 and 20 at connecting regions

5   30 and 32, where the lateral torsional support beam 16 is integral with the substrate to support the cantilever structure 10. The thin, tall segments provide a high spring constant and high rigidity in the vertical direction and are

10   interconnected to provide a laterally rigid structure, as noted above.

As described above, vertical motion of the arm 12 in the direction of arrow 28 produces a twisting motion, or torsional motion, indicated

15   by arrow 50 about the axis 27 of cantilever beam 16 (see Fig. 4). The beam has a high aspect ratio rectangular cross section, with a spring constant:

$$k_z = \frac{3EI}{L_c^3} = E\frac{ab^3}{4L_c^3} \qquad\qquad \text{Eq. (1)}$$

where $I = ab^2/12$ is the second moment of area, a

20   is the width of the beam, b is the height of the beam, and L_c is the length of the moment arm 12 which produces the torsional force (see Fig. 2 and 6). For a rectangular beam experiencing a torque

30

T, the angle of rotation θ about its central axis
(in the direction of arrows 50)is:

$$\theta = \frac{TL_T}{\beta G a^3 b}$$ Eq. (2)

where L_T is the length of the beam 16 between the
mounting point 32 and the nearest support beam 79
which produces the torsional force; G is the shear
modulus of rigidity of the material; and β is a
coefficient determined by the aspect ratio b/a.
For silicon(100), the shear modulus G is
approximately 7.96 x 10^{10} N/m². The following is
a table of coefficients β for various aspect
ratios of rectangular beams:

TABLE I

b/a	1	2	3	4	5	10	∞
$\frac{1}{\beta}$	0.1406	0.229	0.263	0.281	0.291	0.312	0.333

With the torsional cantilever
illustrated in Figs. 1 and 2, a force F_z acting on
the tip 23 in the direction 28 at a distance L_c
from the torsional support beam 16 produces a
torque T defined as:

$$T = F_z L_c$$ Eq. (3)

31

The angle of rotation θ is the deflection ΔZ of the tip in the direction of arrow 28, divided by the length of the cantilever moment arm:

$$\theta = \frac{\Delta Z}{L_c} \qquad \text{Eq. (4)}$$

5   Substituting equations 3 and 4 into equation 2, the effective spring constant $k^\theta{}_z$ of the torsional cantilever beam 16 is:

$$k_z^\theta = \frac{F_z}{\Delta Z} = 2\beta G \frac{a^3 b}{L_c^2 L_T} \qquad \text{Eq. (5)}$$

the factor "2" being included because the specific
10   beam structure 16 illustrated in Fig. 6 includes two axially aligned segments on opposite sides of the center of the beam where the torsional force is applied, both of which are, in effect, rectangular beams mounted as cantilevers to the
15   side walls of mesas 19 and 20.

Fig. 7 illustrates the relationship of a range of effective spring constant values with cantilever length, as a function of the geometric variables a and L_c, with the dimension b held
20   constant at 10 micrometers. Curves 105 through 108 represent values of beam width a equal to 1.5 micrometers, 1 micrometer, 0.5 micrometer and 0.25

32

micrometer, respectively, where the length of the beam L_T is equal to 50 micrometers for curve 105 and 200 micrometers for the remaining curves. These curves indicate that torsional cantilevers fabricated using the SCREAM-I process will achieve spring constants between 10^{-3} and 10^{-7} N/m. It was found that because of the high aspect ratio (b/a) of the beams, they exhibit no curling or buckling.

The theoretical spring constants for a torsional cantilever are shown in the following table:

TABLE II

Force	Deflection	Spring Constant	Ratio to k_z
F_x acting at tip	Δx	$k_x = \dfrac{2Ea^3b}{L_T^3}$	$\dfrac{k_x}{k_z^{\theta}} = \dfrac{E}{\beta G}(\dfrac{L_C}{L_T})^2$
F_y acting at tip	Δy causing a twisting of angle ϕ	$k_y^{\phi} = 3E\dfrac{a^3b}{L_C L_T^2}$	$\dfrac{k_y^{\phi}}{k_z^{\theta}} = \dfrac{3E}{2\beta G}(\dfrac{L_C}{L_T})$
F_z acting at center of mass	Δz	$k_z = \dfrac{2Eab^3}{L_T^3}$	$\dfrac{k_z}{k_z^{\theta}} = \dfrac{E}{\beta G}(\dfrac{b}{a})^2(\dfrac{L_C}{L_T})^2$
F_z acting at tip	Δz causing a rotation of angle θ	$k_z^{\theta} = 2\beta G\dfrac{a^3b}{L_C^2 L_T}$	1

33

The foregoing table also shows the ratio of the theoretical spring constants to the value k^θ_z, where v is the Poisson's ratio of the material, this ratio being equal to 0.28 for silicon(100). The force F_x in the above table acts on the tip 23 in the x direction to cause a deflection along the x axis. Force F_y acting at tip 23 produces a deflection in the y direction and a consequent in-plane twisting of the moment arm 12 about support beam 16 through an angle ϕ, while force F_z acting at tip 23 produces a deflection in the z direction to produce a rotation of angle θ at the support beam 16. When the force F_z acts at the center of mass; i.e., is directed onto the top of beam 16, there will be a deflection of beam 16 equal to Δz. The spring constants of the cantilever structure 10 for these various forces are illustrated in the table. As long as the length L_c of the cantilever arm 12 is longer than the length of the torsional supports L_T, all other spring constants of the torsional cantilever will be one or more orders of magnitude greater than k^θ_z. Although the capacitor plates 46 and 54 are provided to sense relative motion in the z direction, it will be understood that additional capacitor plates or other sensors such

34

as piezoresistors, mirrors, diodes or transistors may be provided to detect motion of the cantilever in various directions.

Torsional resonators fabricated using the SCREAM technique with $k^\theta{}_z$ equal to about 0.3 N/m have achieved Q values of 10^5 in a vacuum. A model of the present invention was constructed in accordance with Fig. 1, with the beam width a equal to 1.5 micrometers, the beam height b equal to 12.3 micrometers, the distance L_T equal to 50 micrometers and the distance L_c equal to 950 micrometers. This structure produced a spring constant of 2.58×10^{-2} N/m. Furthermore, the resonant frequency of the torsional cantilever was experimentally measured at 1.4 kHz. The torsional rigidity was then determined, using the following relationship:

$$f_r = \frac{1}{2\pi}\sqrt{(\kappa/I)}$$
 Eq. (6)

where κ is the torsional rigidity and I is the moment of inertia. The known geometry of the device and the densities of the materials permit calculation of the rotational moment of inertia I $= 2.55 \times 10^{-16}$ kg m^2. The resulting torsional

35

rigidity is $\kappa = 1.97 \times 10^{-8}$ N/m, which means that experimentally $k^{\theta}_z = \kappa/L_c^2 = 2.18 \times 10^{-2}$ N/m.

Fig. 8 illustrates a modification of the cantilever device of Figs. 1 and 2, wherein the
5 counterweight 26 is replaced by a second cantilever moment arm 120 which is a duplicate of moment arm 12 and is coplanar, but extending on the opposite side of support beam 16.   The cantilever moment arm 120 includes segments 122,
10 124, 126, and 128 which correspond to segments 60, 64, 68, and 72 of moment arm 12, with the cantilever structure extending over electrode 54' on the floor 38 of cavity 34.   The symmetric design of Fig. 8 provides improved results for
15 applications such as in a scanning force microscope, since the moment arms of the two cantilevers about support beam 16 are more precisely balanced.   However, the asymmetric design of Figs. 1 and 2 may provide improved
20 results for some sensor applications such as in an accelerometer.   As with Figs. 1 and 2, the electrodes 54 and 54' beneath the structure are used to move the cantilever or to detect motion, or both.

25   A still further embodiment of the invention is illustrated in Figs. 9 and 10,

36

wherein the cantilever device 10 of Figs. 1 and 2

is provided with electrodes adjacent the torsional

support beam 16 for controlling twisting of the

beam under the torsional forces applied by the

5   cantilever arm 12 and the counterweight 26.   In

this illustration, the position of the arm 12 and

counterweight 26 are reversed.   As illustrated, a

first   pair   of   electrodes   140,   142   is   placed

adjacent end 30 of beam 16 while a second pair of

10   electrodes 144, 146 is placed adjacent end 32 of

beam 16.   As the support beam 16 is twisted under

a torsional force, as illustrated in dotted lines

at 16' in Fig. 10, the upper edge 148 of beam 16

will approach electrode 142 and the lower edge 150

15   will approach electrode 140.   A voltage applied to

the electrodes 140 and 142, such as the voltage V

relative to the voltage on beam 16, will attract

the   respective   edges   148   and   150   of   beam   16,

causing the beam to twist further,   so that the

20   applied voltage will affect the spring constant of

the cantilever.

It will be understood that the voltage

may be applied to the electrodes 140, 142 and 144,

146 by way of integrated circuits fabricated on

25   the   substrate   18,   such   as   circuits   generally

indicated at 152 and 154 in Fig. 9, connected by

37

way of conductors 156, 158, and 160, 162, respectively. These electrodes and conductors may be fabricated in accordance with the SCREAM-I process described above.

5   It has been found that the planar configuration of the cantilever moment arms 12 and 120 illustrated in the preceding figures may be subject to some in-plane twisting. In order to sense such twisting, a plurality of comb-type

10   capacitor electrode sets 170, 172, 174 and 176 may be provided, as illustrated in Fig. 11. Each of the electrode sets, such as set 170, may include a plurality of stationary finger electrodes 180 mounted in cantilever fashion to a mesa 181 on the

15   substrate within the cavity 34, which contains the cantilever moment arms 12 and 120. Alternatively, the stationary electrodes 180 may be in the form of mesas, or islands, extending upwardly from the floor 38 of cavity 34. Corresponding interleaved

20   finger electrodes 182 are mounted on the cantilever moment arm 12 for motion with the cantilever arm and with respect to the stationary electrodes 180. The interleaved electrode fingers form capacitors which may be used to sense the

25   motion of the cantilever arms 12 and 120, both within the plane of the cantilevers and out of the

38

plane of the cantilevers. Further, upon application of suitable voltages; for example, through an active feedback circuit (not shown) on substrate 18, motion of the cantilevers can be

5   damped or enhanced to compensate for the twisting of the support beam 16. The comb-type capacitor sets 172, 174, and 176 are similar to set 170.

A still further embodiment of the invention is illustrated in Fig. 12, wherein the

10   electrodes mounted on the floor of the cavity 34 in which the cantilever structure 10 is located are omitted, and in their place are provided comb-type capacitors interacting with the cantilever moment arms. In this embodiment, a comb-type

15   torsional cantilever device 200 is fabricated within cavity 34 in substrate 18, again using the SCREAM-I process described above. The cantilever device 200 is mounted on a torsional support beam 16 which preferably is integral with the substrate

20   18 and is mounted on mesas 19 and 20 in cavity 34, in the manner described above with respect to the device of Fig. 1, for example. The cantilever device 200 includes a pair of elongated moment arms 202 and 204 which are spaced from, and are

25   suspended above, the floor 38 of cavity 34 and are moveable in a direction perpendicular to the plane

39

of the cantilever 200, as described above. The cantilevers 202 and 204 are mounted opposite sides of lateral torsional beam 16.

5   The cantilever moment arm 202 extends from a base region 206 which is mounted on beam support 16 by a plurality of connector beams 208. A plurality of longitudinally-extending, spaced parallel fingers 220 in the form of high aspect ratio beams extend from base region 206. The

10   fingers 220 extend above, and are released from floor 38 and thus are movable with respect to it, are parallel to the longitudinal axis of the moment arm 202, and are coplanar with the moment arm.

15   Interleaved with the fingers 220 are a plurality of stationary fingers 222 which are mounted on mesas 224 and 226 in cavity 34. Fingers 222 extend in cantilever fashion parallel to, and between adjacent fingers 220 and are

20   coplanar therewith. Alternatively, the stationary fingers 222 may be in the form of mesas upstanding from floor 38 of cavity 34 and extending between fingers 220.

           For symmetry, two sets 228 and 230 of

25   interleaved fingers are provided for moment arm 202.   Two sets 232 and 234 of similarly

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interleaved fingers are provided for moment arm
204. The interleaved fingers are fabricated with
metal layers to provide capacitor electrodes which
are connected to external circuity by way of mesas

5   19 and 20 for the movable electrodes and by way of
mesas 224, 226 and 224' and 226' for the
stationary electrodes. Relative motion of
capacitor electrodes 220 and 220' with respect to
the stationary capacitor electrodes 222 and 222'

10   respectively, can be measured to detect vertical
motion of a tip mounted on either of the
cantilever arms 202 and 204, in the manner
described above. Similarly, by selectively
applying voltages between adjacent electrodes, the

15   arms 202 and 204 can be moved, or their response
characteristics varied.

          Modifications of the comb-type drive of
Figs. 11 and 12 are illustrated in Figs. 13-15,
wherein the moveable and fixed interleaved fingers

20   240 and 242, which correspond to fingers 220 and
222 in Fig. 12, are fabricated by the process of
copending application SN 08/383,524, described
above. This process permits fabrication of
partially oxidized released silicon fingers, such

25   as partially oxidized fingers 240 in Fig. 12,
having their upper portions 244 oxidized, with the

41

lower   portions   250   remaining   silicon.
Alternatively, as illustrated in Fig. 14, the
upper portions 248 of the fixed silicon fingers
242 can be oxidized, with the lower portions 250
5   remaining silicon.   A voltage V may be applied
across   the   silicon   portions   of   the   adjacent
fingers to produce an asymmetric electric field
between them which will result in relative motion
of the fingers.   Application of a negative voltage
10   to   the   stationary   fingers   242   and   a   positive
voltage to fingers 240 in Fig. 13 will result in
an upward force on the movable fingers, while the
same polarities applied to the device of Fig. 14
will result in a downward force on the movable
15   fingers.   In Fig. 15, the fingers are provided
with   alternating   oxidized   and   non-oxidized
segments,   the   movable   silicon   fingers   240
including oxidized (silicon dioxide) segments 252,
and   the   fixed   silicon   fingers   242   including
20   oxidized   (silicon   dioxide)   segments   254.   The
oxidized segments on each finger are aligned with
non-oxidized segments on adjacent fingers, so that
by   controlling   the   voltages   applied   to   the
individual   fingers,   either   upward   or   downward
25   motion of the movable fingers can be achieved.

42

Fig. 16 illustrates another embodiment
of the invention wherein two cantilever moment
arms 260 and 262 are mounted within the cavity 34
in substrate 18, in the manner described above.

5   In this embodiment, cantilever arms 260 and 262
both incorporate interleaved sets of capacitor
plates of the type illustrated in Fig. 12,
cantilever arm 260 including capacitors sets 264
and 266, and cantilever arm 262 incorporating

10 capacitor sets 268 and 270 in place of the
underlying electrodes utilized in previous
embodiments. These electrode sets are used to
sense the vertical motion of the cantilever arms
260 and 262 in the manner previously described.

15 In addition, the device of Fig. 16 incorporates
sets of stabilizing comb capacitors to prevent or
to compensate for in-plane twisting, cantilever
arm 260 utilizing stabilizing capacitor sets 272
and 274, and cantilever arm 262 utilizing

20 stabilizer capacitor sets 276 and 278.

Figure 17 is a diagrammatic illustration
of one use of the torsionally-mounted cantilever
device of the invention in an atomic force
microscope. As illustrated, the cantilever device

25 290, which may be any one of the cantilever
devices described above, is mounted adjacent to

43

the surface 292 of a sample 294 that is to be scanned. The sample is mounted on a scanning table 296 which may be driven, as by conventional piezoelectric electric drivers, in an XY plane

5   beneath and parallel to the cantilever 290. The sample should also be adjustable in the Z direction to move it into proximity with a sensor tip 298 carried by the cantilever. When the tip is positioned very close to the surface of sample

10   294, the tip will interact with the material of the surface to produce deflection of the cantilever 290, as is known in the art of atomic force microscopes. The deflection of the cantilever may be detected by sensor 300 which

15   produces an output signal through a feedback loop 302 to control the operation of the scanner 296. The cantilever of the present invention is extremely sensitive and thus allows measurements of extremely small forces with great accuracy.

20   Instead of mounting the sample for motion, or in addition to doing so, the cantilever device itself can be mounted for motion in an XY plane, with the torsional movement of the cantilever producing motion in the Z direction.

25   Such an xy mounting is illustrated in the photomicrograph of Fig. 18 to which reference is

44

now made. In this embodiment, a cantilever structure 310 is mounted on a torsional support beam 312 in the manner described above. The outer ends of beam 312 are mounted on a movable frame

5   314 which is generally rectangular, having four sides, with each side carrying a set of moveable comb-capacitor fingers. Thus, for example, frame side 316 carries capacitor fingers 318.

Stationary capacitor fingers, such as

10 the fingers 320 are mounted on an outer frame 322 and are interleaved with fingers 318. The outer frame number 322 is secured by spring arms 324 to a substrate so that upon energization of the capacitors made up of interleaved fingers 318 and

15 320, the frame 314, and thus the torsional cantilever device 310, will be moved along the longitudinal axis of cantilever 310, in a direction perpendicular to support beam 312. In similar manner, capacitor set 330 also moves the

20 cantilever device along its longitudinal axis, which may be referred to as the X axis of the device.

Capacitor sets 332 and 334 are located on opposite sides of frame 314 at the ends of the

25 beam 312, and when energized tend to move the frame 314 along the axis of beam 312, which may be

45

referred to as the Y direction. Torsional motion
of cantilever 310 about beam 312 provides motion
of the sensor tips carried by the cantilever in a
direction perpendicular to the XY plane to provide
5   Z-direction motion of the tip.

Although Figure 18 illustrates just a
single cantilever mounted within a frame movable
in the X and Y directions, the structure can be
expanded to provide an array of cantilevers, in
10   the manner illustrated in Fig. 19.   As there
illustrated, a 10x10 array of torsional cantilevers
340 are mounted in a 1 millimeter by 1 millimeter
square frame 342, with the cantilevers being spaced
at 100 micrometer intervals.   Each cantilever is
15   mounted on a torsional beam, such as beam 344 of
cantilever 340, between parallel frame elements such
as the frame elements 346 which are parallel to the
X axis of the array. The individual cantilever arms
are located between spaced, parallel Y-axis frame
20   elements such as elements 348. The entire structure
is fabricated by the SCREAM process described above,
and is released from the underlying substrate is
mounted on the substrate for motion in the x-y
plane. Suitable spring arms such as those described
25   above with respect to Fig. 18 may be provided to
secure the structure to the substrate.

46

18 may be provided to secure the structure to the substrate.

On each of the sides of frame 342 are one or more comb capacitor frame driver sets such as those illustrated at 350 and 352, each of which contains movable capacitor fingers connected to movable frame 342 and stationary capacitor fingers mounted on a stationary frame or substrate 354. If desired, frame 354 may carry multiple sets of stationary comb capacitor fingers which engage corresponding fingers carried by extensions of frame 342. Thus, for example, the stationary frame 354 and the movable frame 342 may carry comb capacitor driver sets 356, 358, 360 and 362. These additional sets of comb capacitors increase the distance which the frame 342 can be moved in the X-axis direction and increase the precision of operation so that the cantilevers 340 can be precisely positioned. Similar comb capacitor drivers are provided at each of the four sides of the array, the driver sets indicated at 364 cooperating to provide motion on the X-axis with similar structures (not shown) on the remaining two sides of the array providing motion in the Y axis.

47

Each of the sensor tips on the individual cantilevers 340 are connected to suitable switching and control logic circuits, illustrated generally at 366 and 368. The

5   connections are by way of the frame elements 346 and 348 in the manner described with respect to the movable stage device described in U.S. Patent No. 5,506,175 of Zhang et al. As there described, the frame elements are constructed of multiple

10   interconnected parallel beams with oxidized segments at selected locations to provide electrical paths between the switching and control circuits 366 and 368 and control capacitors and sensors for corresponding individual cantilevers.

15   A major advantage of the array of Fig. 19 is that an area 1 mm x 1 mm can be scanned by moving individual tips only 100 micrometers along their x and y axis. This allows very rapid scanning of a large area without the need for

20   large scale motion.

             Although the various capacitor structures described above may be used for sensing the movement of the cantilever device of the present invention, a piezoresistor sensor may be

25   utilized in place of, or in addition to such capacitor sensors, if desired. Figs. 20 and 21

48

illustrate such piezoresistor sensors for the
cantilever arm 12 of Fig. 1, although it will be
apparent that similar sensors may be used for any
of the torsional cantilever devices described

5   above. Accordingly, in Fig. 20, the moment arm 12
is shown as connected to the torsional support
beam 26 by connector beams 76-79 and the
counterbalance 26 is shown as being connected to
the beam 16 by connectors 80-83, all as described

10   with respect to Fig. 1. The beam 16 is connected
at its ends 30 and 32 to mesas 19 and 20,
respectively.

In accordance with this embodiment of the
invention, a piezoresistor sensor is built into

15   the torsional support beam to measure the
deflection of the cantilever. The piezoresistive
effect is the change in resistance of a conductor
when it is subjected to a mechanical strain, and
in this case, the resistor is defined by

20   implanting an n-type region into a p-type
substrate (or in the alternative, by implanting a
p-type region into an n-type substrate) in the
region of the beam 16 and mesas 19 and 20 prior to
fabrication of the cantilever device. The device

25   is then fabricated using the SCREAM-1 process, as
described above, with the torsional support beam

49

16 located in the implanted region. The top surface of the beam and the mesas is covered with an oxide layer 380, and vias 382 and 384 are opened through the oxide layer to expose the

5   surface of the n-type substrate silicon on the mesas 19 and 20, respectively. Another implant through these vias then defines highly doped regions 386 and 388 to provide contact areas. Aluminum is then sputtered on to the structure and

10   patterned to provide aluminum contacts 390 and 392, in the vias, and these contacts are then connected to external circuitry, as by way of wires (not shown) bonded to the aluminum contact 390 and 392 and to corresponding contacts on

15   sensor circuitry located on the adjacent substrate. The beam 16 then acts as a resistor connected between the contacts 390 and 392.

When a force interacts with the torsional cantilever, a torque is generated about

20   the central axis of the torsional support beam 16. The stress in the beam produces a change in its resistance, and this change can be detected by incorporating the beam resistor in a Wheatstone bridge in the circuitry carried on the substrate.

25   The measured resistance change can be directly related to the amount of deflection of the

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cantilever, and thus to the force which generated

the torque.

Another stress-sensitive sensor, which

is based on the piezojunction effect, is

5   illustrated in Figs. 22 and 23.   When silicon

devices such as diodes and transistors are

subjected to stress, the characteristics of these

devices are affected; more particularly, when

stresses are applied to a pn-junction, the band

10   gap of the junction decreases and the diffusion

length increases.   This increases the saturation

current and leads to a higher forward current for

the same forward bias voltage.   In the embodiment

illustrated in Figs. 22 and 23, advantage is taken

15   of this effect by incorporating a diode into the

torsional support beam 16 of the torsional

cantilever device 10 of Fig. 1. The deflection of

the cantilever is then monitored by the change in

the current of the diode.

20   In Figs. 22 and 23, a pair of sensor

diodes are formed by implanting n+ regions, such

as regions 400 and 402, in a p-substrate silicon

at the junctions 30 and 32 of the torsional

support beam 16 with fixed mesas 19 and 20.

25   Alternatively, a p+-type regions may be implanted

into an n-type substrate silicon.   After formation

51

of the beam 16 and the mesas 19 and 20 using the
SCREAM-1 process described above, vias 404 and 406
are opened in the top oxide layer 408 of beam 16
and mesas 19 and 20 to permit contact to be made

5   to the implanted region. This contact is obtained
by sputtering of aluminum at 410 and 412 on the
mesas and over the doped regions exposed by the
vias 404 and 406.

A second contact to the diode is by way of a

10   p+ region 414 and an aluminum contact 416 located
on the adjacent substrate 18 at a location near to
the mesas 19 and 20. As illustrated in Figs. 20
and 21, the two diodes are located at the
junctions of the torsional support beam 16 with

15   the fixed support for the beam.   When a force
interacts with the torsional cantilever, a torque
is generated about the central axis of the
torsional support beam 16. The stress in the beam
is maximized at the junctions 30 and 32, and this

20   stress acts on the diodes to cause a change in the
current in each diode.   The measured current
change can be directly related to the amount of
deflection of the cantilever, and subsequently to
the force which generated the torque.   The

25   aluminum contacts are connected as by wire leads
bonded to the contacts, to corresponding contacts

52

in adjacent circuits to provide the requisite measurements.

Although the present invention has been described in terms of numerous embodiments, it
5   will be apparent that variations and modifications may be made without departing from the true spirit and scope thereof as set forth in the following claims.

53

What is claimed is:

1.   A force sensor, comprising:

a single-crystal silicon substrate;

a   torsionally-mounted   cantilever
including a moment arm and a support beam formed
from said substrate and integral therewith, said
cantilever moment arm being responsive to a force
to be measured for motion about said support beam
with respect to said substrate; and

detector   means   for   detecting   said
motion.

2.   The force sensor of claim 1, further
including an integrated circuit on said substrate
electrically connected to said detector means.

3.   The force sensor of claim 1, wherein
said detector means is on said substrate and
includes at least one electrode capacitively
coupled to said moment arm.

4.   The force sensor of claim 3, wherein
said moment arm includes at least one electrode
capacitively coupled to said detector means on
said substrate.

54

5. The force sensor of claim 4 wherein said at least one electrode on said substrate includes plural stationary electrode fingers, and wherein said at least one electrode on said moment arm includes plural movable electrode fingers interleaved with said stationary fingers.

6. The force sensor of claim 5, wherein said cantilever has a predetermined spring constant, and further including a capacitor adjacent said support beam for adjusting said spring constant.

7. The force sensor of claim 1, wherein said cantilever has a predetermined spring constant and further including capacitive means for adjusting said spring constant.

8. The force sensor of claim 1, wherein said detector means includes a comb-type capacitor having a first plurality of fingers mounted on said cantilever and a second plurality of fingers mounted on said substrate, said fingers being interleaved.

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9. The force sensor of claim 8, wherein said first and second capacitor fingers comprise partially oxidized single crystal silicon.

5   10.   The force sensor of claim 9, wherein each said capacitor fingers includes plural spaced partially oxidized segments located in alignment with corresponding nonoxidized segments in an adjacent fingers.

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             11.   The force sensor of claim 1, further including an integral sensor tip on said moment arm.

15   12.   The force sensor of claim 1, wherein said cantilever further includes a counterweight formed from said substrate and integral with said support beam.

20   13.   The force sensor of claim 1, wherein said moment arm and said counterweight are coplanar with, and are perpendicular to, said support beam, extend in opposite directions from said support beam, and are movable with respect to
25   said substrate to twist said support beam in response to a force applied to said moment arm.

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14. The force sensor of claim 13, wherein said cantilever is fabricated from said substrate in the form of single crystal silicon beams having cross-sectional aspect ratios of

5   about 10 to 1, to provide mechanical rigidity in the direction of forces applied to said moment arm.

15. The force sensor of claim 14,

10   further including driver means for electrically controlling twisting of said support beam.

16. The force sensor of claim 15, wherein said driver means is a capacitor.

15

17. The force sensor of claim 14, further including driver means for electrically controlling motion of said moment arm.

20   18. The force sensor of claim 17, wherein said driver means is a comb capacitor.

19. The force sensor of claim 1, wherein said detector means comprises a first

25   metal electrode deposited on said substrate, said first electrode being substantially parallel to

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and spaced from said moment arm and a second metal electrode deposited on said moment arm.

20. The force sensor of claim 1, further including:

a movable frame carried by said substrate, and wherein said support beam includes first and second ends mounted on said frame for securing said support beam.

21. The force sensor of claim 20, further including multiple support beams mounted on said frame, each of said support beams including a corresponding moment arm to form an array of counterlevers torsionally mounted within said frame.

22. The force sensor of claim 21, wherein each cantilever is mounted for independent motion with respect to said frame.

23. The force sensor of claim 1, wherein said detector means includes a piezoresistive sensor responsive to torsional forces applied to said support beam.

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24. The force sensor of claim 1, wherein said detector means includes a pn junction responsive to torsional stress in said support beam.

5

25. A method of detecting forces comprising mounting a high aspect ratio elongated, horizontal, cantilevered support beam, on a substrate; mounting an elongated, high aspect

10 ratio horizontal moment arm on said beam with said moment arm being at right angles to and coplanar with said beam;

applying a force to be detected to said moment arm in a direction to produce a twisting of

15 said beam with respect to said substrate; and

detecting motion of said moment arm with respect to said substrate.

26. The method of claim 25, further

20 including electrically adjusting the spring constant of said beam.

27. The method of claim 25, wherein detecting the motion of said moment arm includes:

25 fabricating a first electrode on said moment arm,

59

fabricating a second electrode on said substrate adjacent said first electrode; and

measuring changes in the capacitance between said first and second electrodes.

5

28.   The method of claim 27, further including electrically adjusting the spring constant of said beam.

10   29.   The method of claim 28, further including electrically controlling horizontal motion of said moment arm.

FIG.1

FIG.2

3/16

FIG.3(a) — Photoresist, Oxide/Nitride/Oxide, Silicon

FIG.3(b) — Oxide/Nitride/Oxide, Silicon

FIG.3(c) — Oxide/Nitride/Oxide, Oxide, Silicon

FIG.3(d) — Oxide/Nitride/Oxide, Oxide, Silicon

FIG.3(e) — Oxide/Nitride/Oxide, 24, 23, Oxide, Silicon

FIG.3(f) — Oxide/Nitride/Oxide, TiW, Oxide, Silicon

FIG.3(g) — Oxide/Nitride/Oxide, Planarizing resist, TiW, Oxide, Silicon

FIG.3(h) — TiW, Oxide, Silicon

SILICON
WAFER
WITH
DEVICES

MOTOR

57

18

56

METAL

METAL
EVAPORATION
SOURCE

FIG. 4(a)

56

58

58

d

18

SUBSTRATE

FIG. 4(b)

10

58

58

58

12

62

60

FIG. 5

FIG. 6

FIG. 7

Effective Spring Constant vs. Cantilever Length (b=10um)

6/16

FIG.8
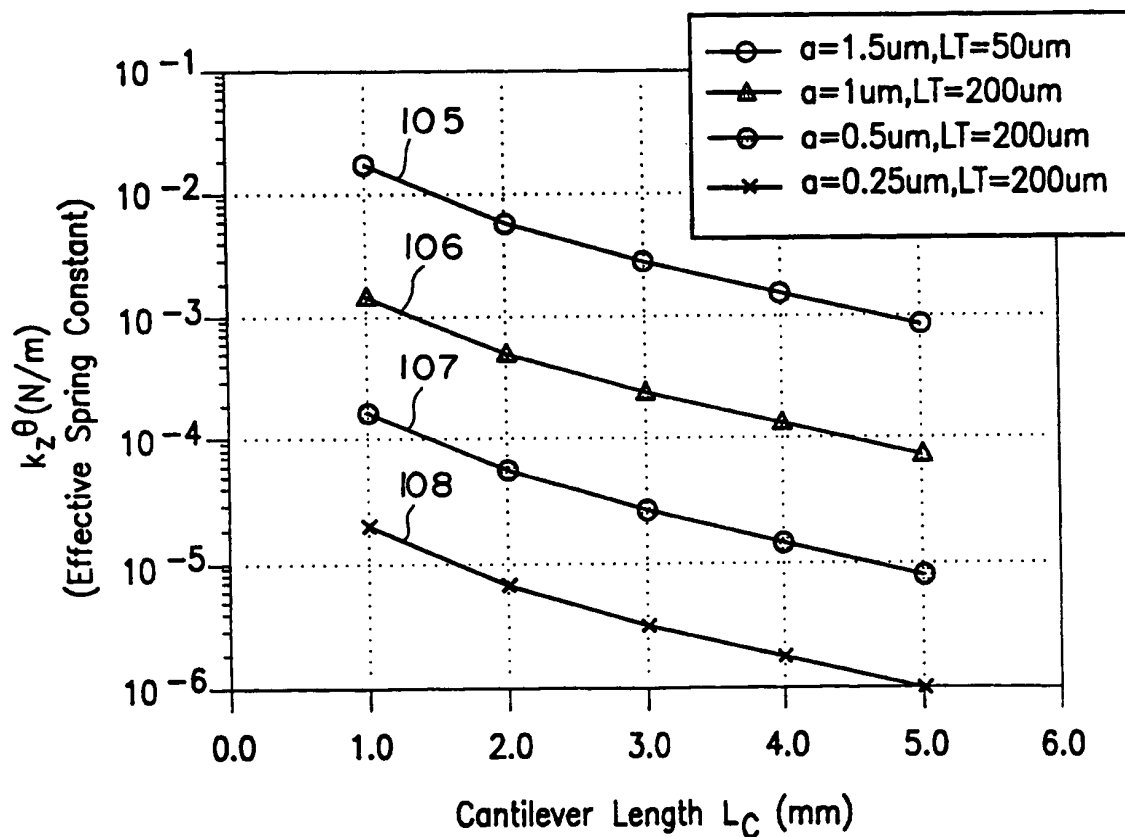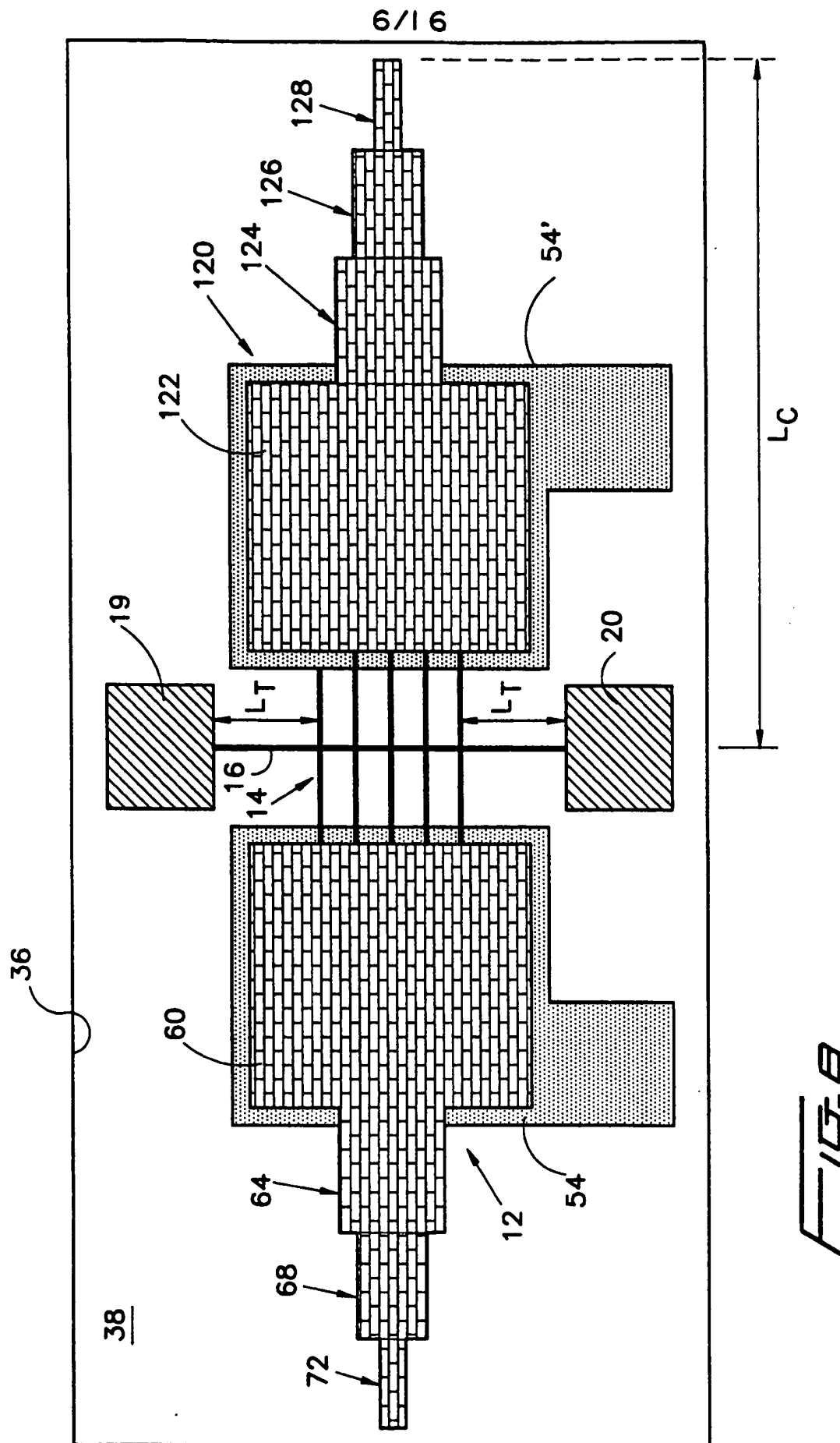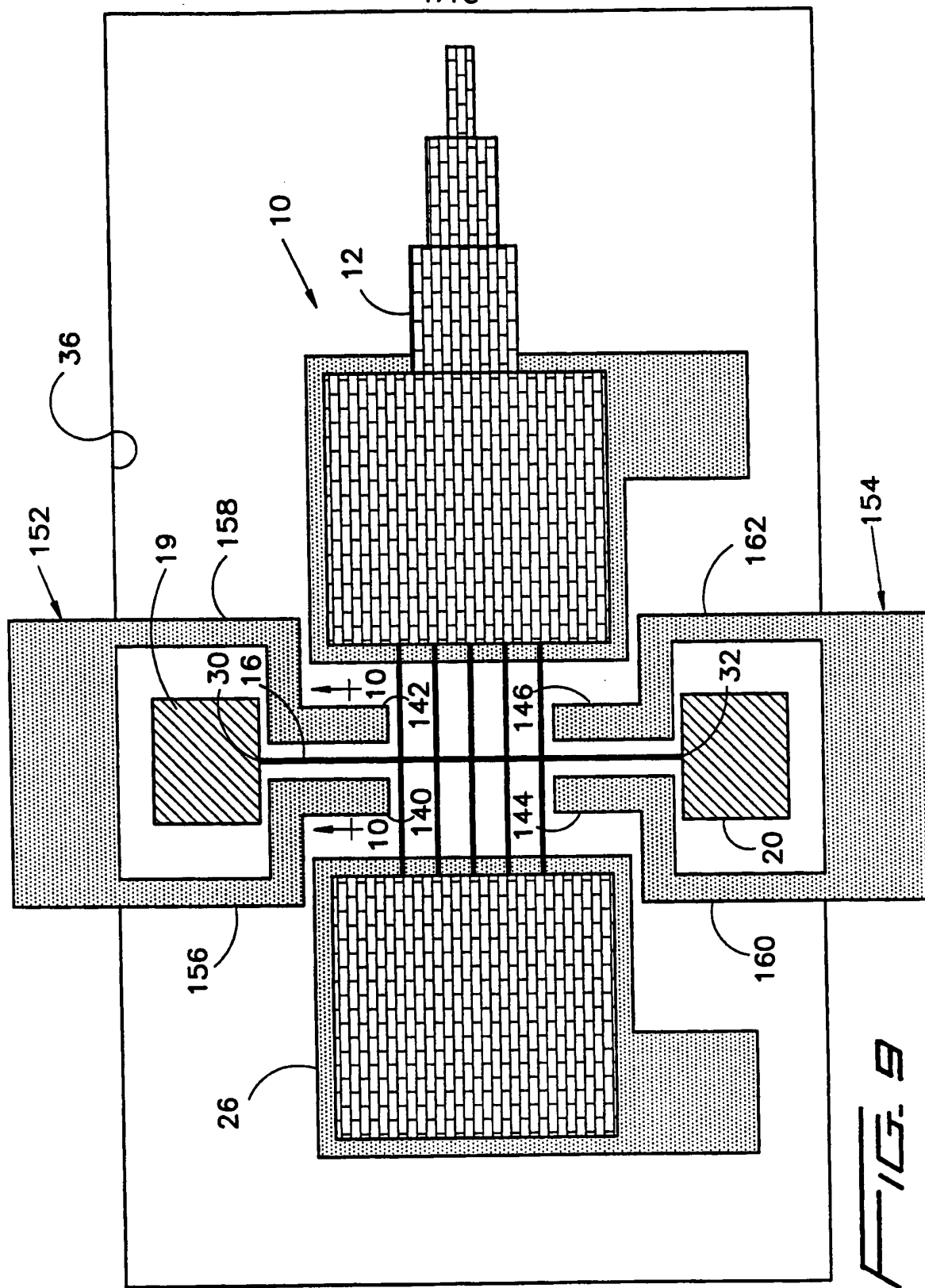
FIG. 9
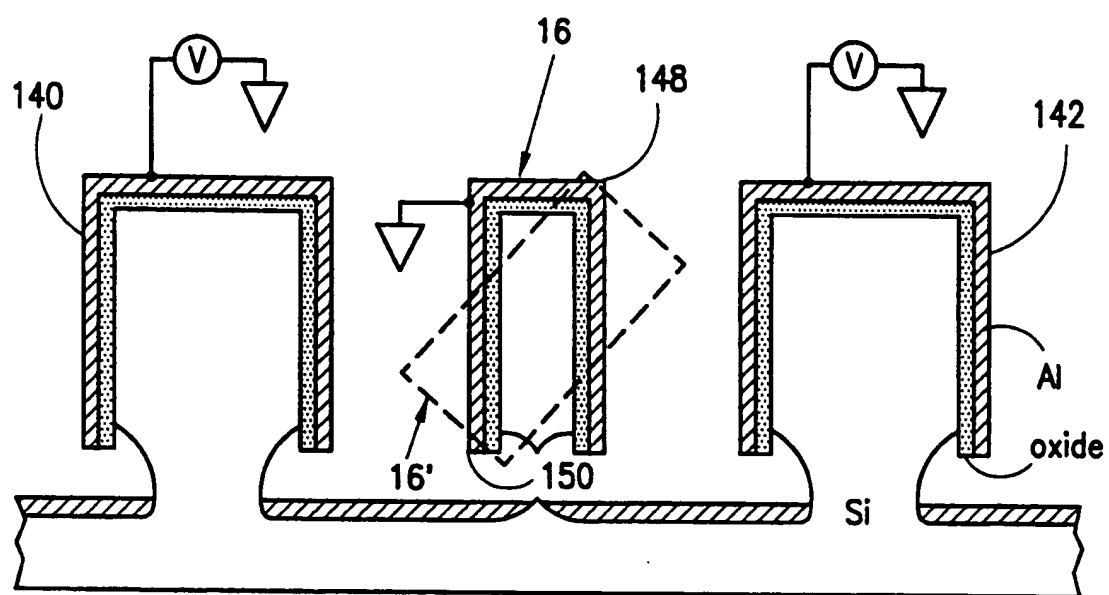
FIG. 10
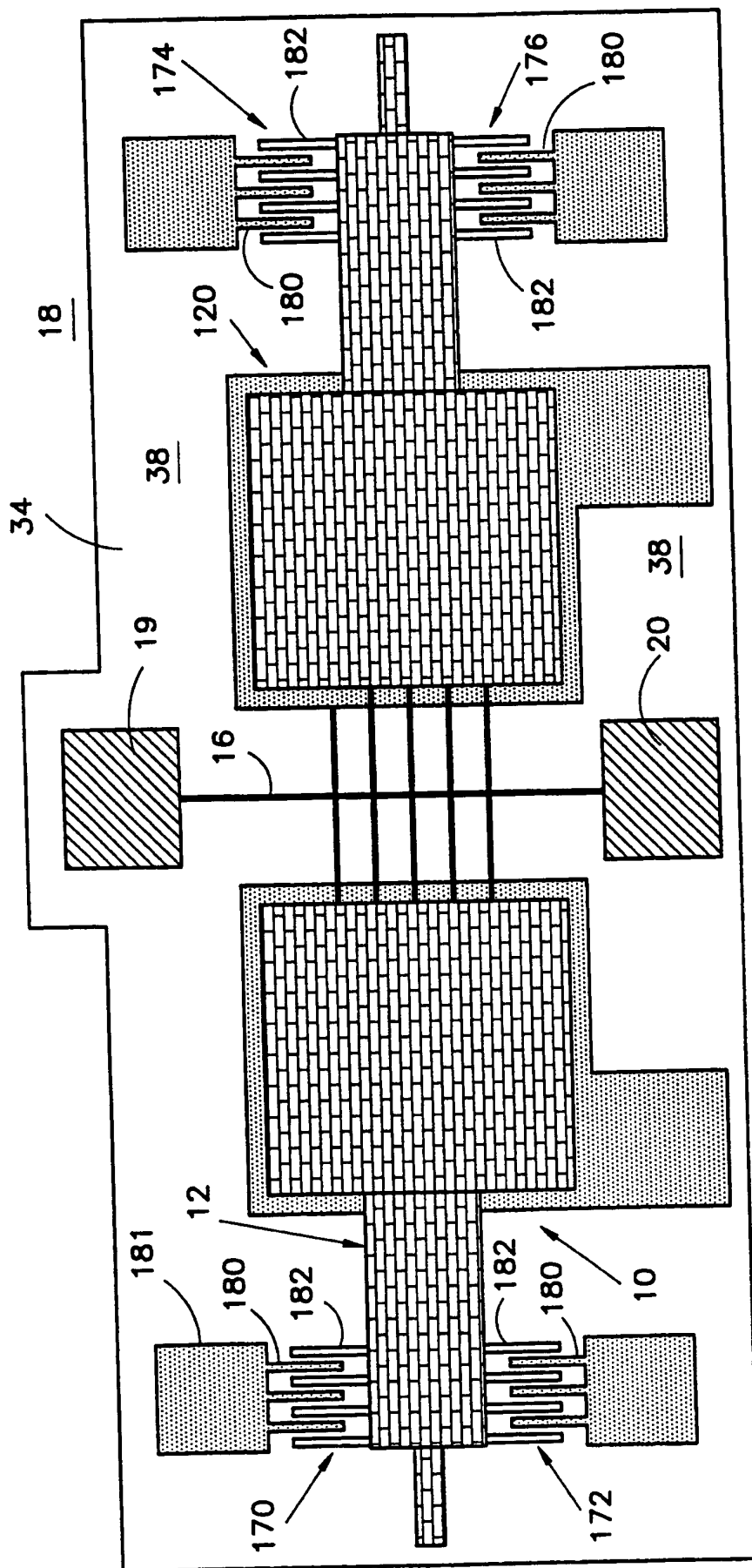
FIG.11
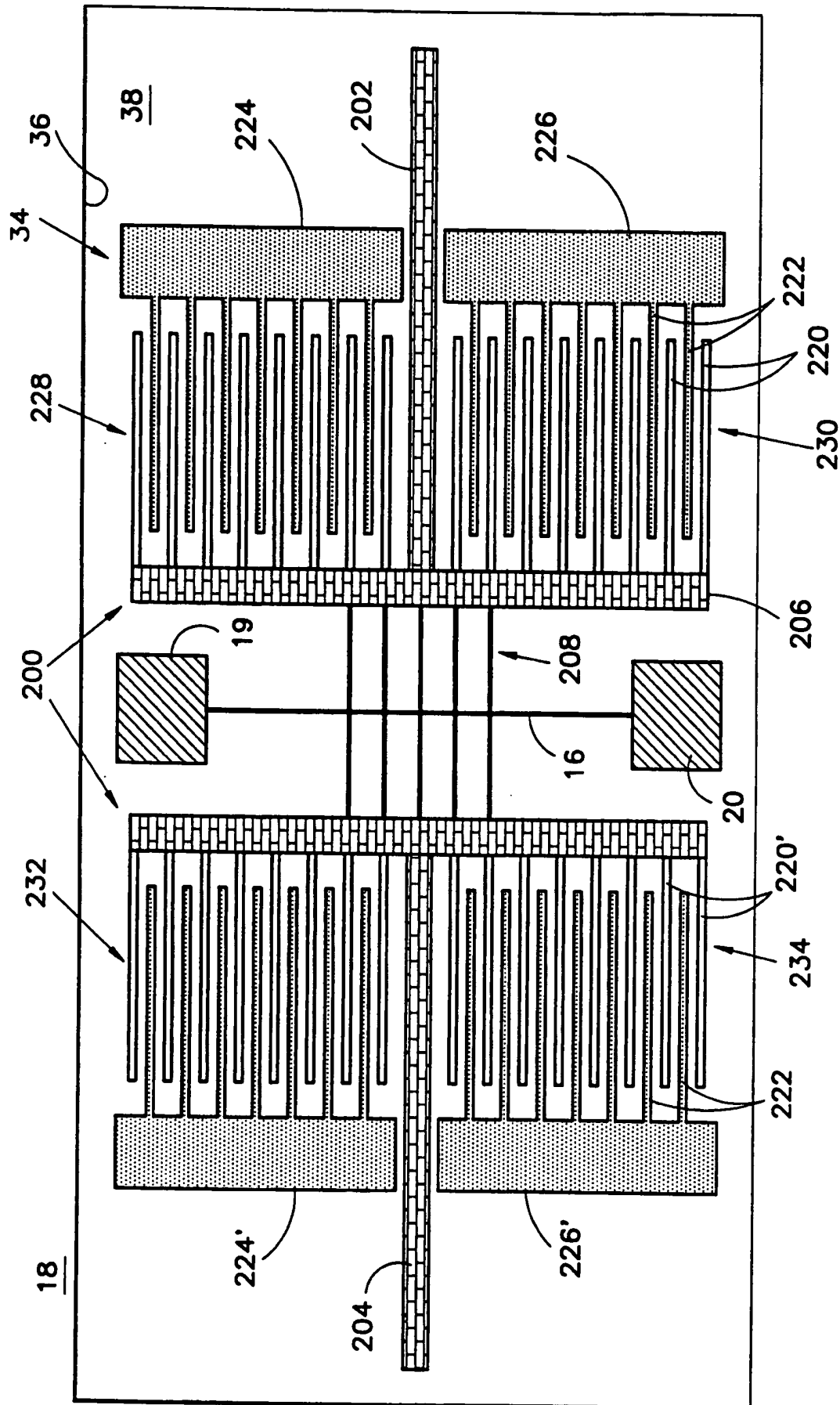
FIG. 12
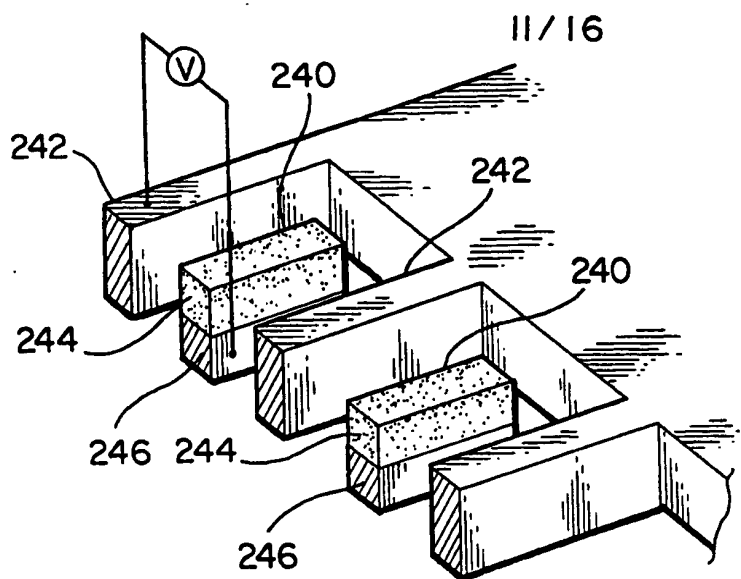
FIG.13
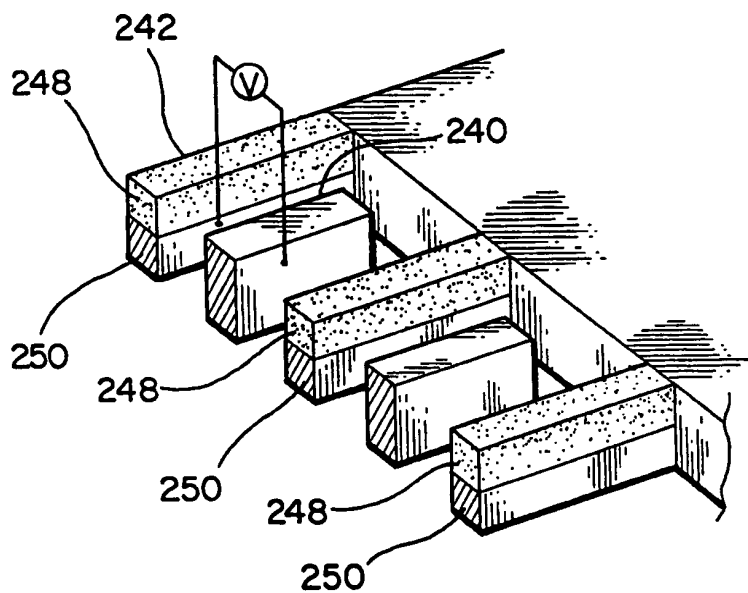
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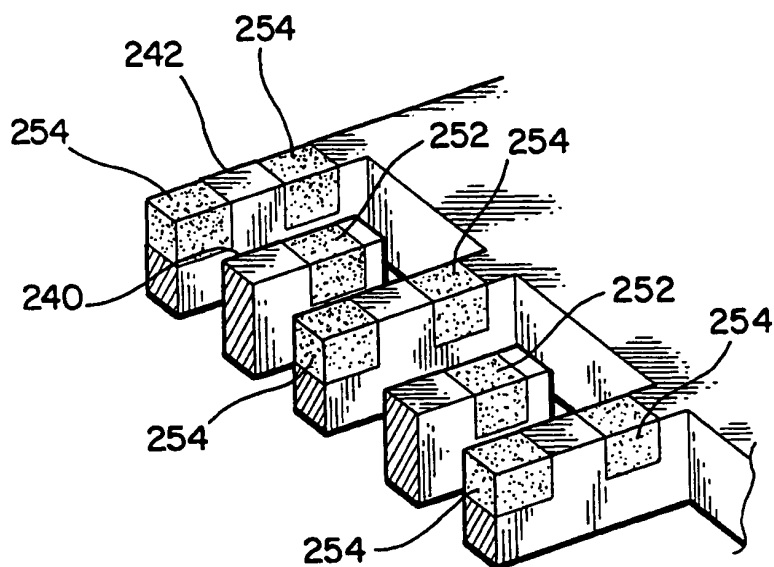
FIG.15

12/16

FIG.16

FIG.17

FIG.18

FIG. 19

Switching and Control Logic

15/16

Al contact
20 392 78
32 79
21
384
388
82
83
n+ region
18

10 12 18

76
77 16
390 19 386

Al contact

80
81 30 382
26

n+ region

Al contact

p+ region

FIG. 20

392 Al contact 16 380 oxide Al contact 390 n+ region

n+ region n- type region

20 388 386

p- substrate 19

18

FIG. 21

18

20

Al contact

n+ region

406
402

32

412

12

79

78

76

77

n+ region

16

83

82

81

30
400

80

19

10

18

Al contact

404

410

p+ region

416

414

Al contact

FIG. 22

n+ region

412

20

Al contact
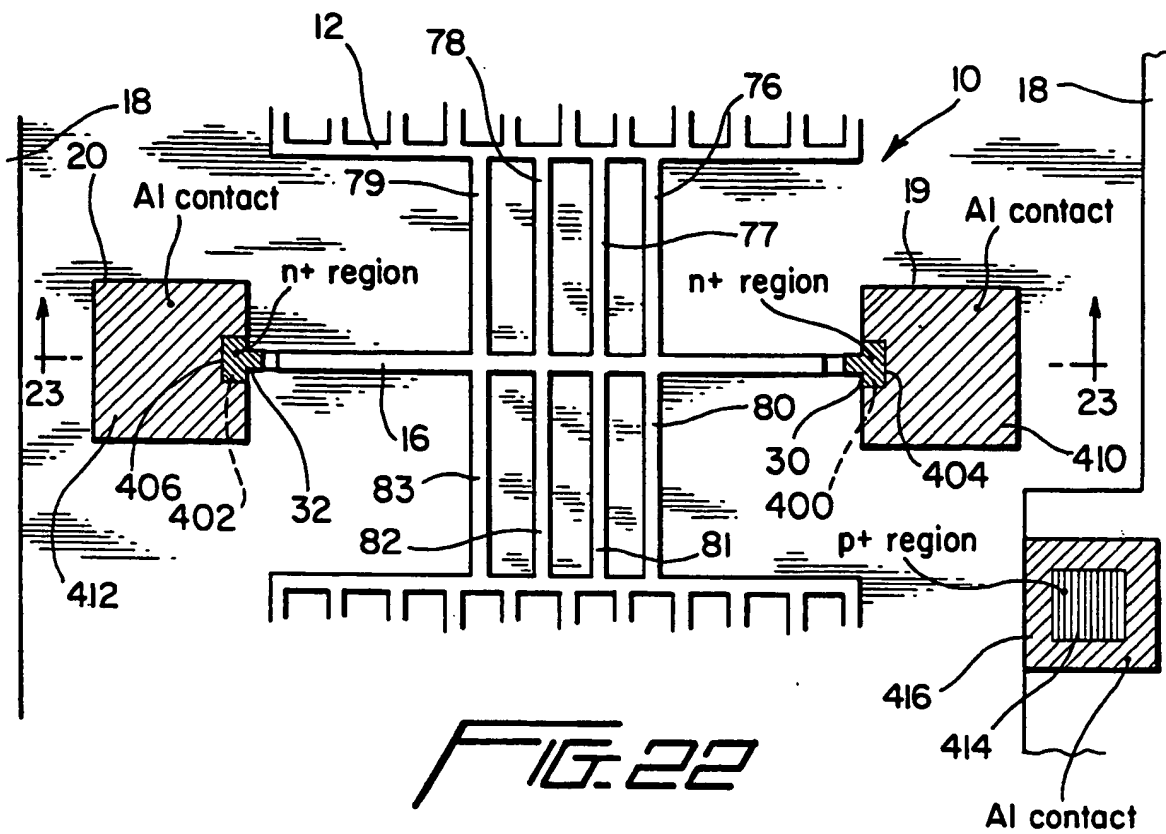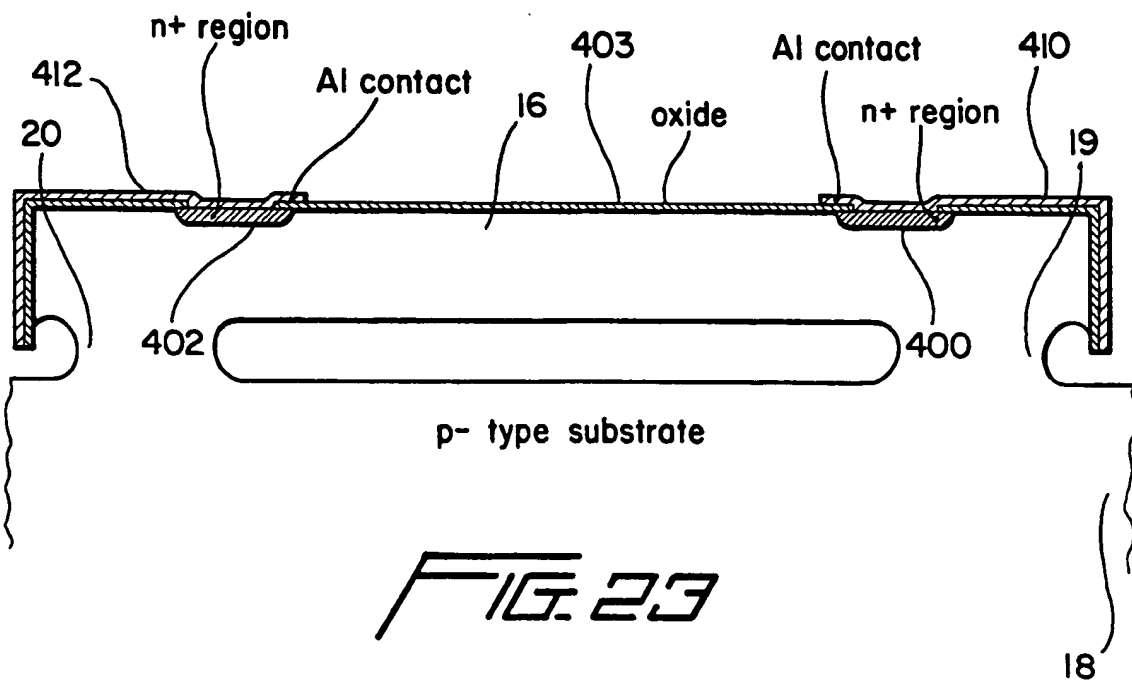
403

16

oxide

Al contact

n+ region

410

19

402

400

p- type substrate

18

FIG. 23

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